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FURTHER INVESTIGATION OF LANDING SITE REDESIGNATION DURING THE LEM POWERED DESCENT

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SUMMARY

A study is presented of the required guidance commands and available footprint for landing site redesignation during the final approach phase (Phase II) of the LEM powered descent. Redesignations are initiated between 11,000 and 5,000 ft altitude off a nominal descent trajectory. This study, based on a variable time-to-go, indicates that a nearly circular footprint of about 10,000 to 20,000 ft. radius is available for a ΔV penalty of 100 fps. Time-to-go is calculated as a function of range and range rate. Therefore, a redesignation that decreases the range may destroy the constancy of the guidance commands for the nominal Phase II flight. These command variations, in some instances, cause interruptions in the visibility of the landing area and also produce command rates near design control limits. However, any increase in range results in small changes in the guidance commands and the visibility of the landing area is very good.

INTRODUCTION

The LEM powered descent is divided into three phases (see figure 1); an initial braking phase (Phase I), final approach (Phase II), and the landing phase (Phase III). Phases I and II of the LEM powered descent are guided by a set of equations which are reported in reference 1. The landing approach flight is a near constant thrust and attitude trajectory designed to allow adequate fuel economy, pilot control, and pilot visibility of the landing area, as presented in reference 2. The initial and final conditions and the time of flight of Phase II are predetermined to yield this constant attitude and constant thrust phase of flight. In the event that the predetermined landing site is deemed unsatisfactory by the pilot, he then has the capability for redesignating the landing area during Phase II. However, since the time-of-flight (time-to-go) was specified in order to yield a constant thrust vector profile for guiding to the preselected site, the time-to-go must also be redesignated or variations in the thrust profile will result as reported in reference 3. It is the purpose of this study to investigate a method of redesignating time-to-go. Namely, defining time-to-go as a function of range and range rate, i.e., $T_{GO} = 2R/\dot{R}$. A landing footprint or area available for alternate site selection is determined based on this concept of a redesignated time-to-go.

SCOPE OF CALCULATIONS

The nominal powered descent trajectory used for this study is initiated at an altitude of 50,000 feet with a zero flight path angle and a velocity of 5,583 fps, which define the state vector at pericynthion for a Hohmann descent transfer from an 80-n.mi orbit. A time history of Phase I is presented in figure 2(a). Phase II is assumed to begin at an altitude of 11,069 feet and incorporates a constant attitude of 47 degrees from the negative horizontal axis (see figure 3 for axis system) and a thrust level of 4,874 lbs., as compared to a full throttle thrust of 10,500 lbs. A time history of Phase II is shown in figure 2(b). The terminal conditions are 10 fps velocity and -10 degrees flight path angle at an altitude of

200 feet. Although this trajectory is only one of a number of possible nominal powered descent trajectories, it is believed that the data acquired is representative of data which would be obtained from other nominal trajectories.

The primary guidance equations reported in reference 1 are used to calculate the required guidance commands to approach the terminal conditions at the alternate landing site selected. The equations of motion are based on a point mass. The guidance constants are updated every second and there is no updating less than 10 seconds prior to termination.

Time-to-go is calculated assuming a constant acceleration along the relative range vector. This assumption is based on the near constant thrust magnitude and direction. Therefore, the acceleration component along the relative range vector is defined in equation (1).

$$\ddot{R} = k \qquad (1)$$

The integrals of equation (1) can be written as follows:

$$\dot{R} = k\,T_{GO} + \dot{R}_o \qquad (2)$$

$$R = k\,T_{GO}^2/2 + \dot{R}_o\,T_{GO} + R_o \qquad (3)$$

Solving equations (2) and (3) simulataneously and using the initial conditions $R_o = \dot{R}_o = 0$ the time-to-go is determined as

$$T_{GO} = 2R/\dot{R} \qquad (4)$$

Equation (4) is used to redesignate time-to-go when the terminal conditions have been changed.

Changes in the landing site are indicated at three different ranges; 43,607 feet, 30,492 feet, and 19,510 feet with an altitude of 11,069 feet, 7,812 feet, and 5,078 feet, respectively. Changes in down range distances of about ± 40,000 feet and cross range distances to about 30,000 feet were considered.

RESULTS AND DISCUSSION

Area Available - The preselected landing area first becomes visible after the pitchup maneuver at nominal range of 43,607 feet (altitude - 11,069 feet) at the beginning of Phase II. The maximum landing area footprint is applicable for the case where an alternate site selection is made immediately (see figure 4). It should be noted that this footprint and all others presented herein are symmetrical about the down range axis. For convenience only half of the footprint is shown. This maximum or ideal footprint shows that for a ΔV penalty of 100 fps from a nominal range of 43,607 feet, the range may be lengthened by about 10,000 feet, shortened by about 30,000 feet, and a cross range distance of over 15,000 feet may be reached. The shaded area of figure 4 is not available because the maximum thrust of 10,500 lbs. is exceeded in order to satisfy the final desired conditions. Other possible constraints such as limited bank angles have not been considered.

To allow adequate time to assess the landing area it is assumed that the alternate landing site selection should be initiated at some nominal range between 30,000 feet and 19,000 feet. The landing area will then have been visible from 20 to 40 seconds. After 20 seconds of Phase II flight a nominal range of 30,492 feet has been reached and the footprint from this altitude is presented in figure 5. This more realistic altitude for a landing site change permits a long range of about 8,000 feet, short range of approximately 19,000 feet, and a cross range of about 12,000 feet for a ΔV penalty of 100 fps. As in figure 4, the shaded area may not be obtained because the maximum thrust is exceeded.

The resulting range after a 40 second assessment is 19,510 feet. The area available from this range is depicted in figure 6. For a ΔV penalty of 100 fps from a 19,510 foot range, the available range is an additional 6,000 feet and a short range of about 8,000 feet. Again the shaded area is not available because of the maximum thrust limitations.

A previous study was made by holding the time-to-go constant at the value predicted by the guidance logic for the nominal trajectory (see reference 3). The two methods of prescribing time-to-go results in approximately the same landing area, however, the footprints are shifted along the down range axis, for example, the constant time-to-go results in a larger down range capability for a ΔV penalty of 100 fps.

The variations of the guidance commands associated with the present footprints and landing site visibility are discussed in the following two sections.

Guidance Command Variations - By predesignating the initial and final condition and the time of flight, a constant attitude and constant thrust of the Phase II flight are obtained (using the primary guidance equations reported in reference 1). A change in any one of these characteristics would necessarily destroy this constancy, therefore, violating the nominal design criteria of this portion of the LEM powered descent. This situation occurs when an alternate site selection (a change in the final conditions) is made. To present the variations in guidance commands after the alternate site selection has been made, the following three typical off-nominal trajectories are calculated from each of the initial ranges: (a) a 10,000 ft range extension, (b) a 10,000 ft short range, and (c) an out-of-plane case of 10,000 ft cross range.

Time histories of the pitch angle for the trajectories (a), (b), and (c) together with the nominal range of 43,607 ft are shown in figure 7(a).

The maximum pitch angle rate (nearly a constant rate for the coplanar cases) is about .25 deg/sec from this altitude. Figure 7 is continued by portraying the thrust magnitude in figure 7(b). The maximum thrust rate is about 25 lbs/sec and, again, a near constant rate for the coplanar cases. The yaw angle, which is measured from the north as shown in figure 3, is presented in figure 7(c), and is -90° for all coplanar cases. For the out-of-plane case, the yaw angle rate is about .6 deg/sec. These variations do not seem to be operationally sever, but do become larger for redesignations at the two shorter ranges investigated.

The pitch angle, thrust magnitude, and yaw angle from a range of 30,492 feet are shown in figures 8(a), 8(b), and 8(c), respectively. For an alternate site selection made at this range, the pitch angle rate increases to .5 deg/sec, the thrust magnitude rate to about 40 lbs/sec and the yaw angle rate to about .7 deg/sec.

From the shortest range of 19,510 feet, the pitch angle thrust magnitude and yaw angle time histories are presented in figures 9(a), 9(b), and 9(c). These trajectories result in the highest guidance command rates, since the alternate site selection was delayed until a later time. The maximum pitch angle rate for these trajectories is about 1.5 deg/sec with a maximum thrust magnitude rate of approximately 65 lbs/sec. Also, the yaw angle rate is about 1.8 deg/sec.

These guidance command variations still do not seem to be operationally severe but may result in spacecraft attitudes that prevent visibility of the landing site. The command variations resulting from a constant time-to-go (as reported in reference 3) are slightly larger for an increase in the range, and smaller for a decrease of the range.

Visibility of the Landing Site - One of the design constraints of the Phase II flight is adequate visibility of the landing area. The lower window limit of visibility is 25 degrees above the -x body axis (negative thrust vector) of the LEM (see figure 3). Time histories of the look angle or line-of-sight angle to the landing site, which is assumed to be 1,000 feet down range from termination of Phase II, are presented in figures 10(a), 10(b), and 10(c) for the three redesignation points investigated. These figures show that for a short range landing area, visibility of the landing area is lost immediately but regained later in the descent trajectory. For any range extension (cross range or down range), the visibility is very good throughout the trajectory. However, based upon the ΔV limitations, only one gross change in the landing area may be permitted. If this is the case, the immediate loss of the landing site following a short range redesignation may not be a severe limitation. But, if visibility at all times is a requirement, an alternate site should be chosen giving a range extension, insuring good visibility for the entire trajectory.

The loss of visibility resulting from a constant time-to-go (as reported in reference 3) is for a shorter period of time than that resulting from a recalculated time-to-go. However, visibility was lost near the termination after a range extension (cross range and down range) using a constant time-to-go, where as, the visibility was very good through the entire trajectory using a recalculated time-to-go.

CONCLUDING REMARKS

A study has been presented of the required guidance commands and available footprint for alternate landing site selection during the final approach phase (Phase II) of the LEM powered descent. Redesignations were initiated between 43,607 and 19,510 feet range off a nominal descent trajectory. It was found that a nearly circular area of about 10,000 to 20,000 feet radius could be reached for a ΔV penalty of 100 fps. The alternate site selection resulted in variations of the thrust profile (attitude and magnitude) for the nominal Phase II flight and, in some instances, these variations interrupted the visibility of the landing area. In the present study these variations were not as severe as those encountered in reference 3 in which the time-to-go was held constant. It is also noted that the two methods of prescribing time-to-go results in approximately the same landing area, however, the footprints are shifted along the negative down range axis for $T_{GO} = 2R/\dot{R}$.

It should be stated that the method of calculating time-to-go in this study is not necessarily the best one. Other methods are being investigated at this time and the study will continue.

REFERENCES

1. Cherry, George W., A Class of Unified Explicit Methods for Steering Throttleable and Fixed-Thrust Rockets, MIT/IL, Report R-417 (Rev. 1964).

2. Bennett, Floyd V., Price, Thomas G., Study of Powered-Descent Trajectories for Manned Lunar Landings, NASA TN D-2426, 1964.

3. Price, Thomas G., Investigation of Landing Site Redesignation During Phase II of the LEM Powered Descent Using Primary Guidance, MSC IN 65-EG-20, May 18, 1965.

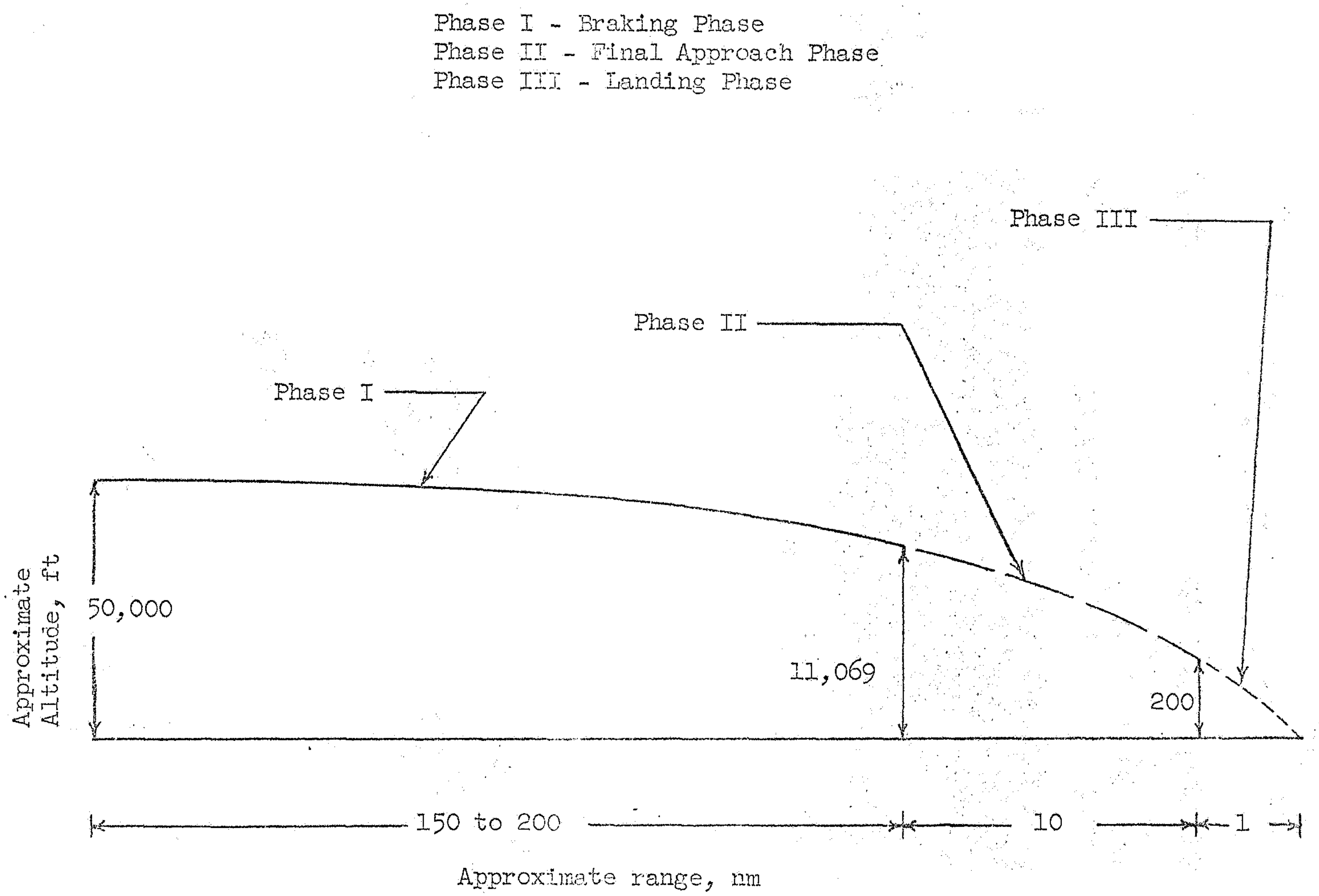

Figure 1 - Three Phases of Powered Descent

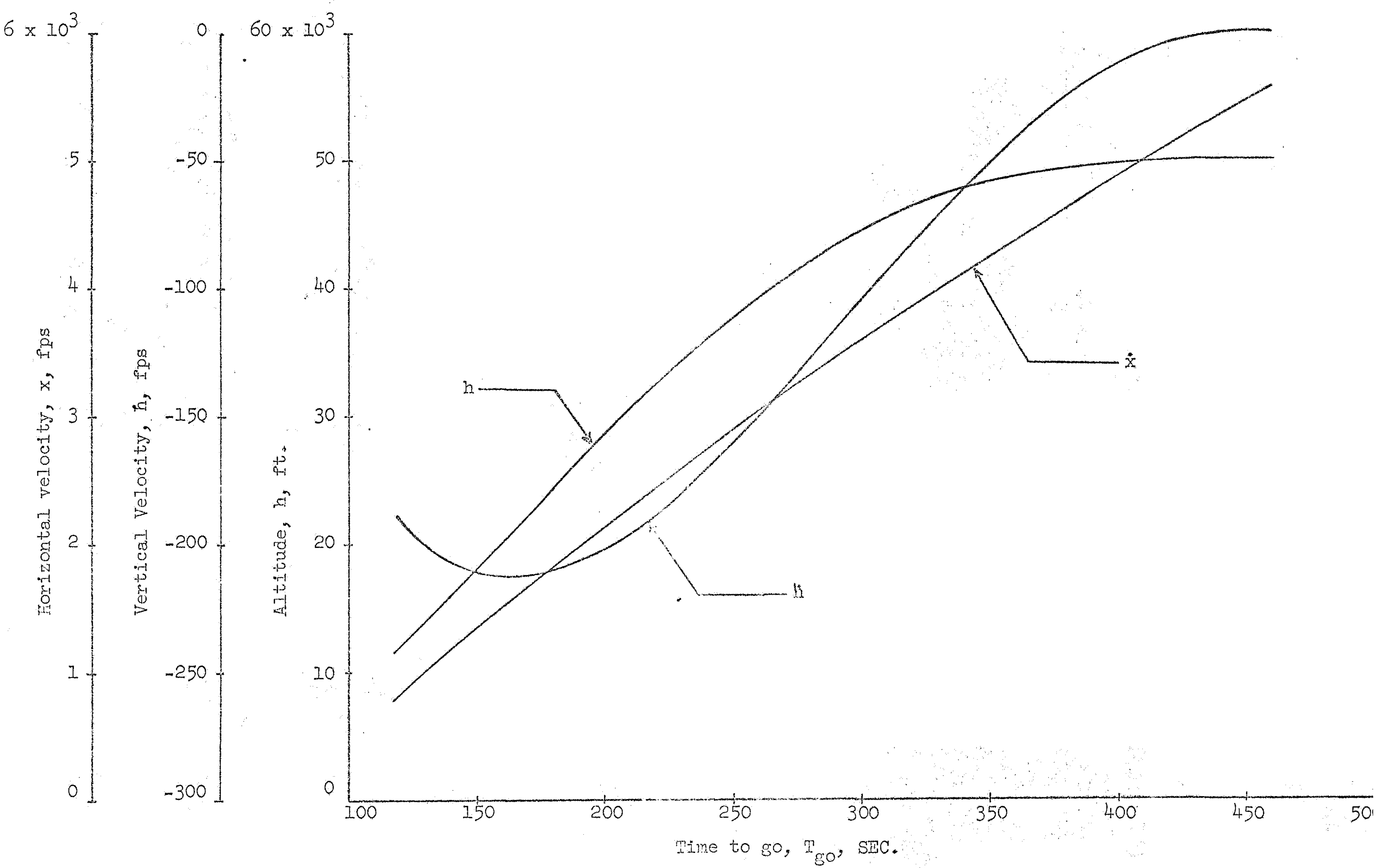

Figure 2 - Time History of Powered Descent
(a) Phase I

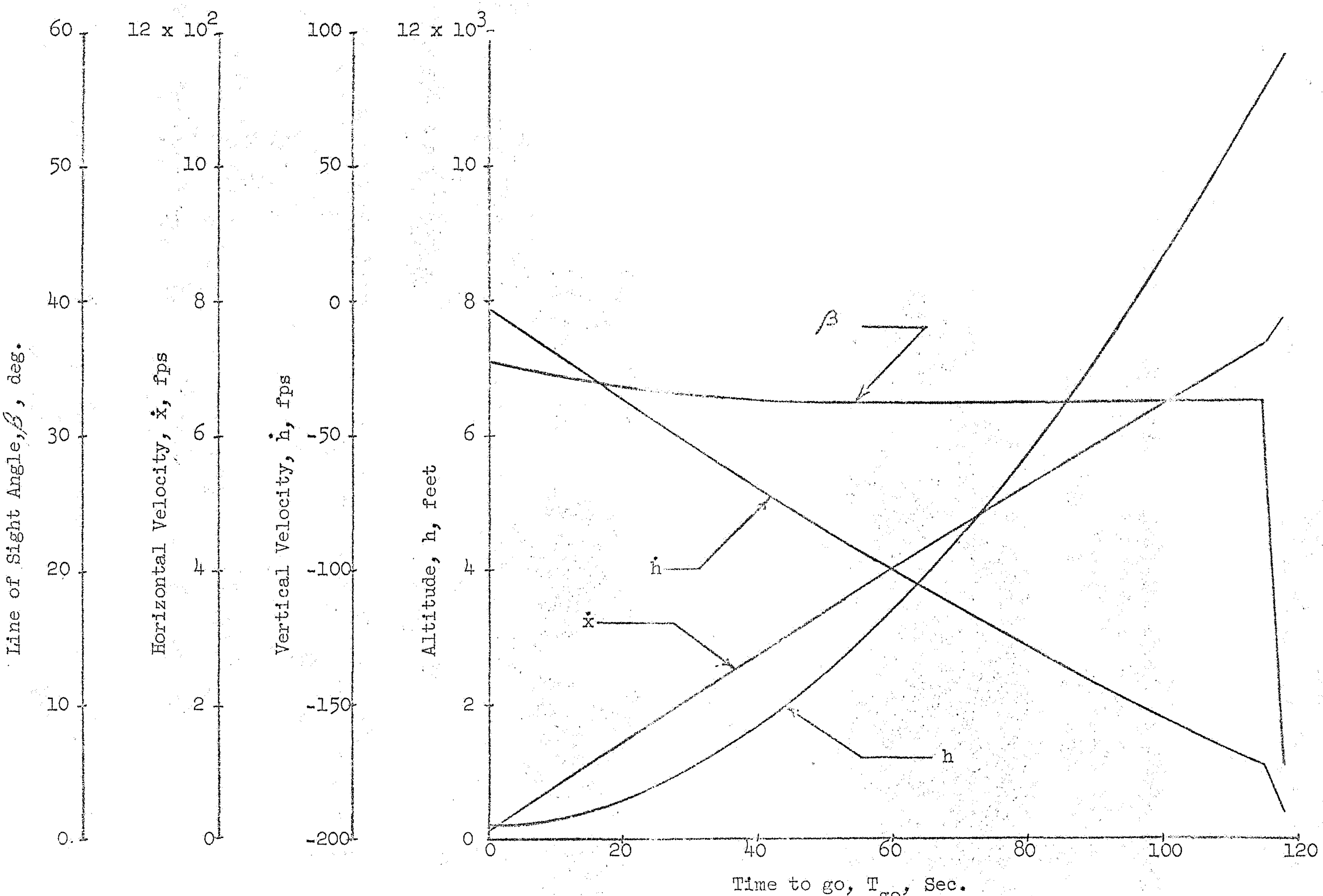

Figure 2 (concluded)
(b) Phase II

β - Look angle

χ_p - Pitch angle

χ_y Yaw angle

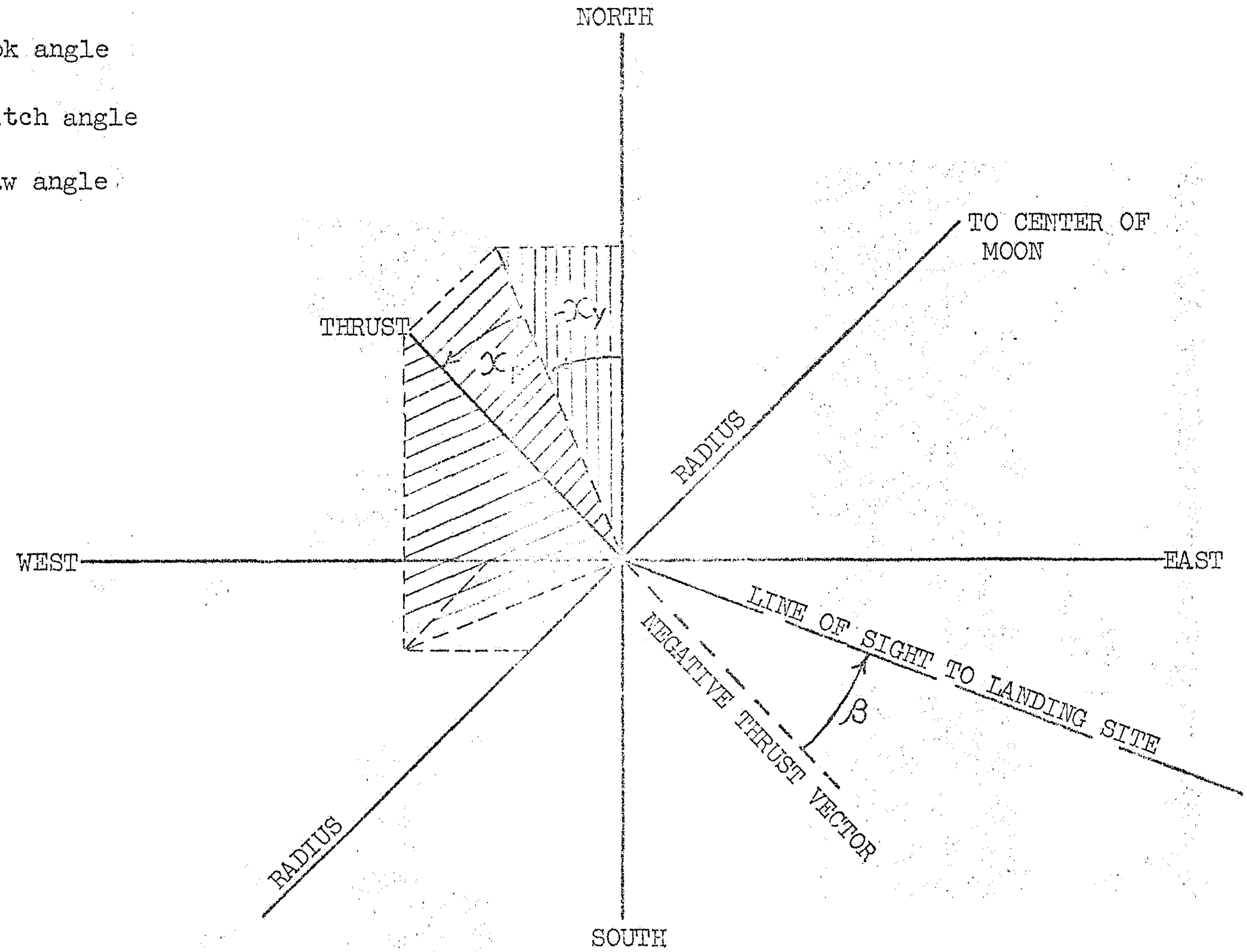

Figure 3.- Sketch of Axis System

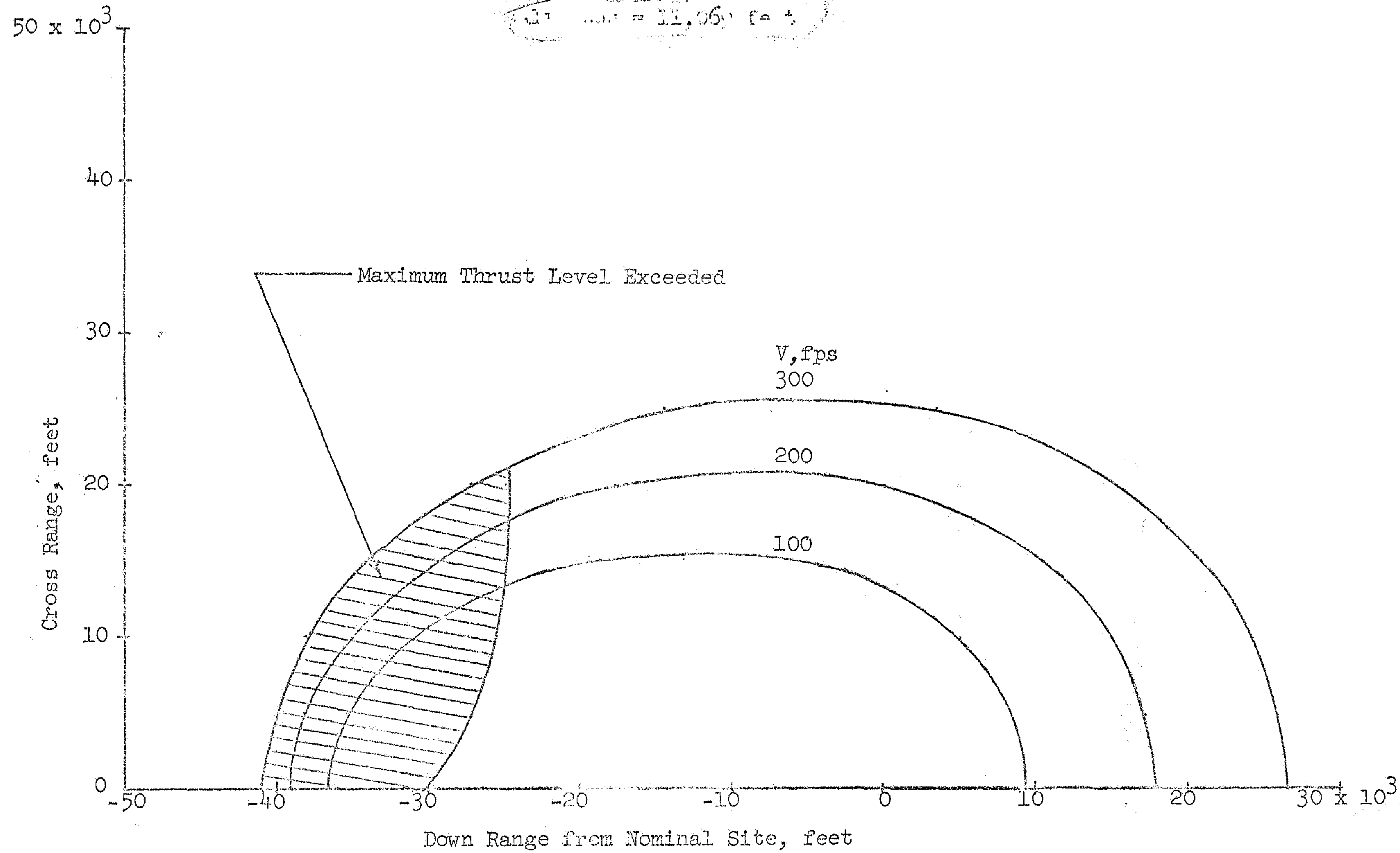

Figure 4 - Footprint with Nominal Range of 43,607 feet (Altitude = 11,069 feet.)

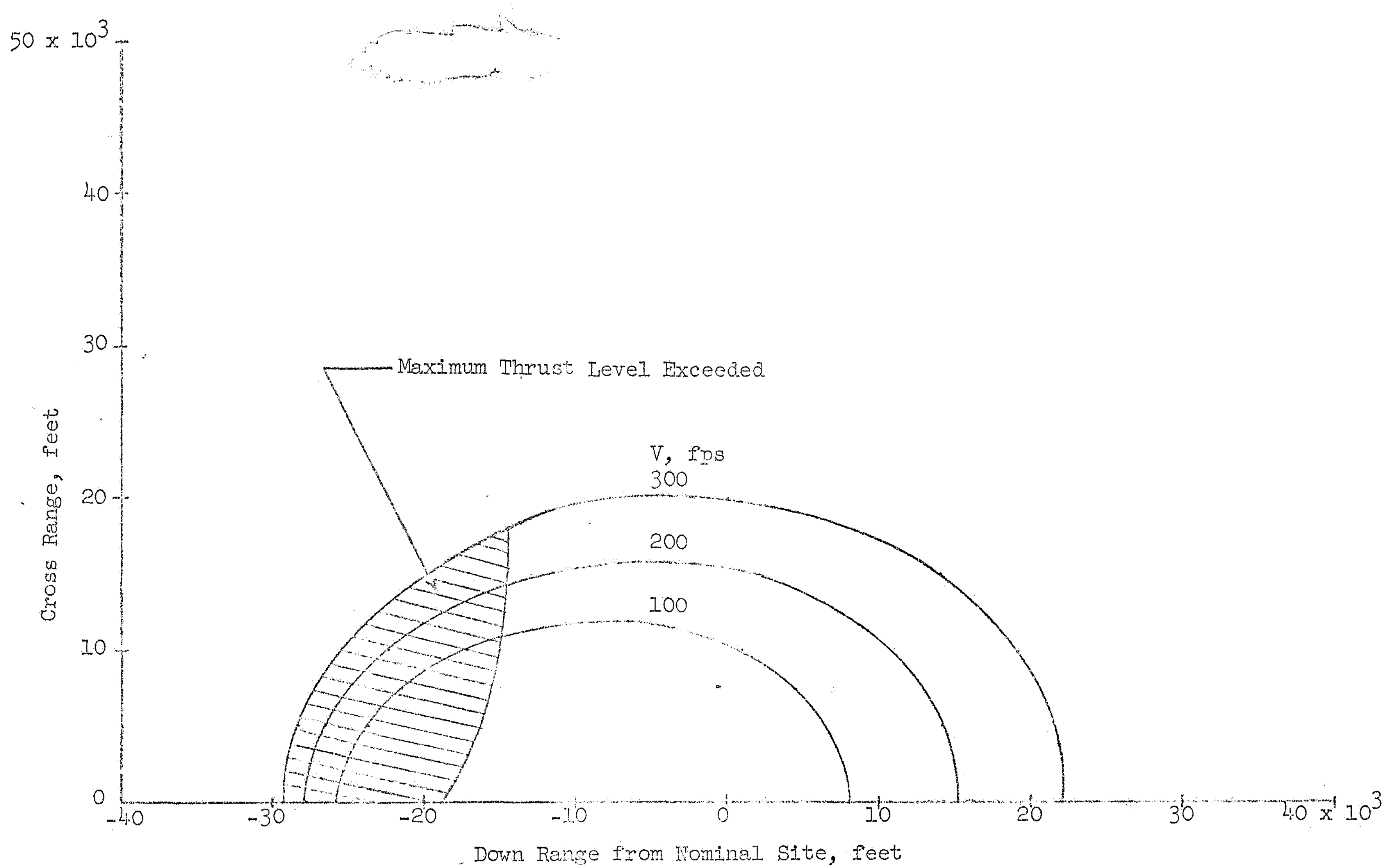

Figure 5.- Footprint with nominal range of 30,492 feet (Altitude = 7812 feet)

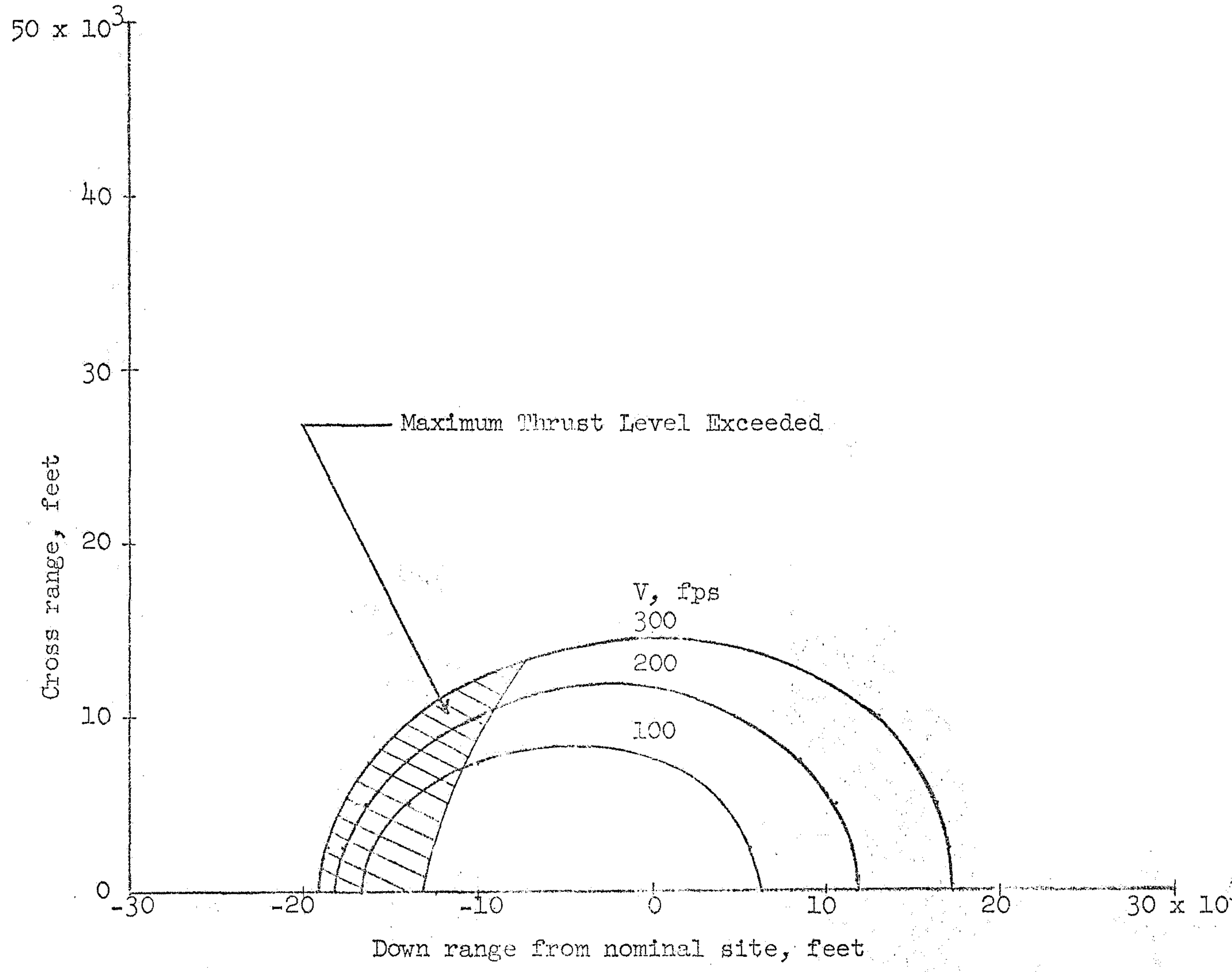

Figure 6.- Footprint with nominal range of 19,510 feet (Altitude = 5078 feet)

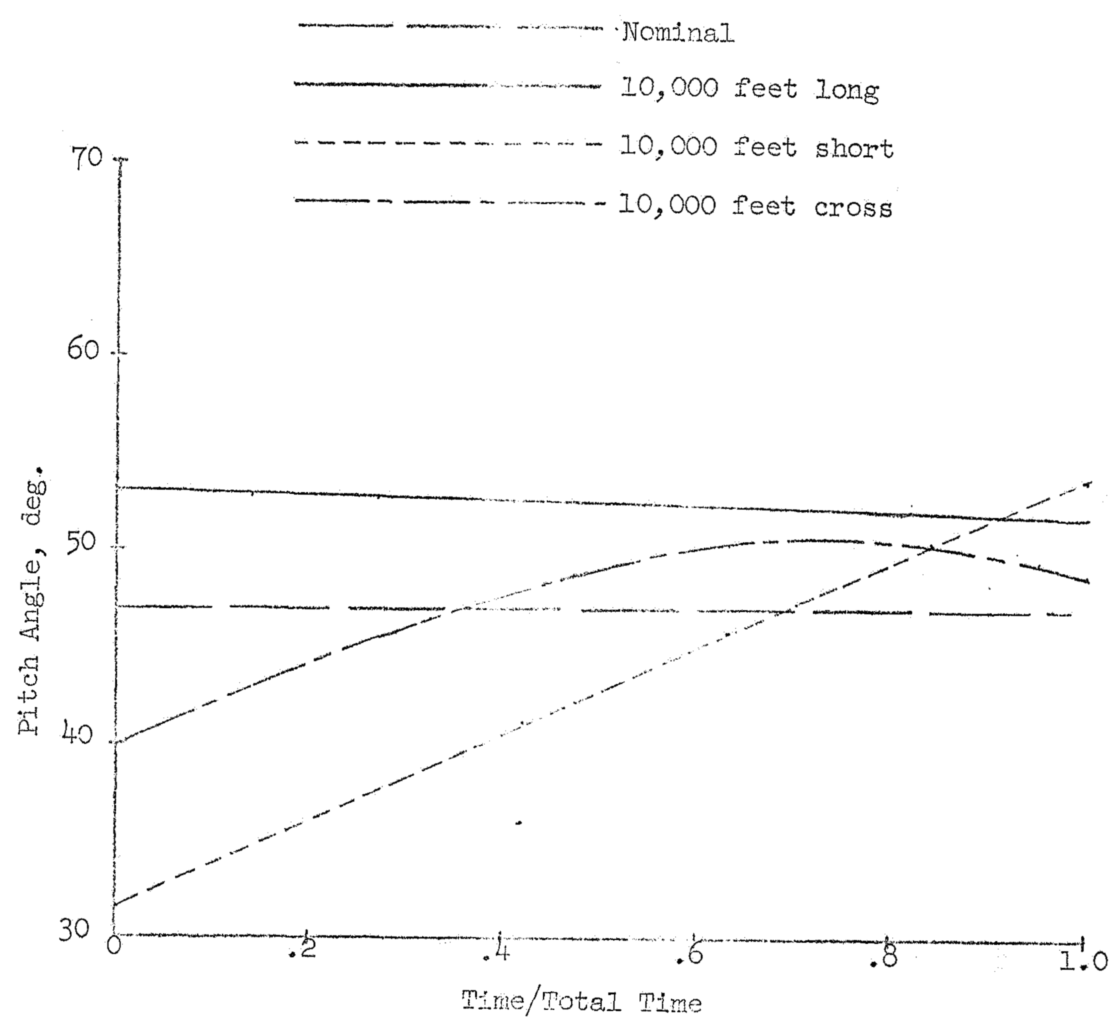

Figure 7 - Time history of guidance commands for alternate site selection from range = 43,607 feet.

(a) Pitch Angle

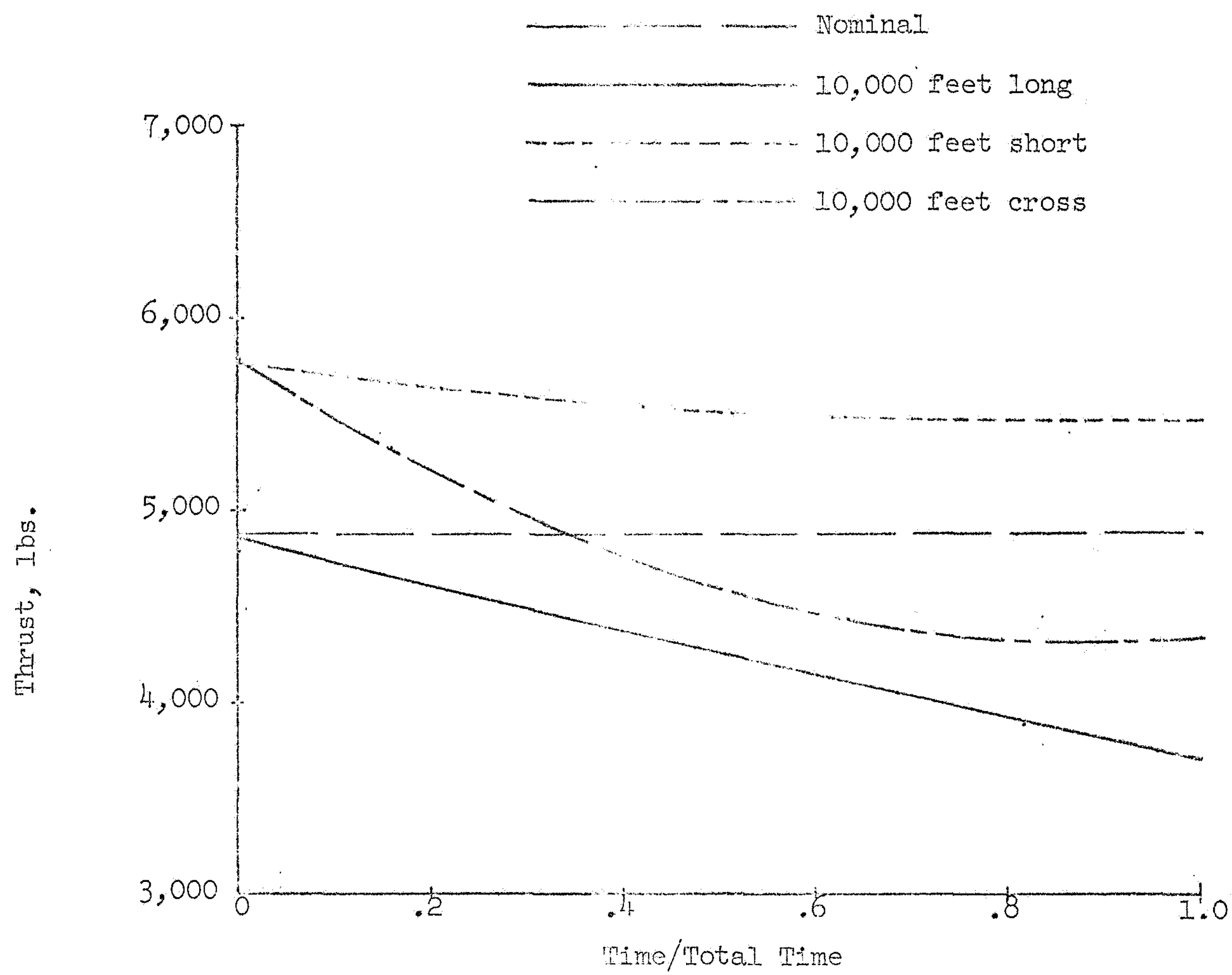

Figure 7 - (Continued)
(b) Thrust Magnitude

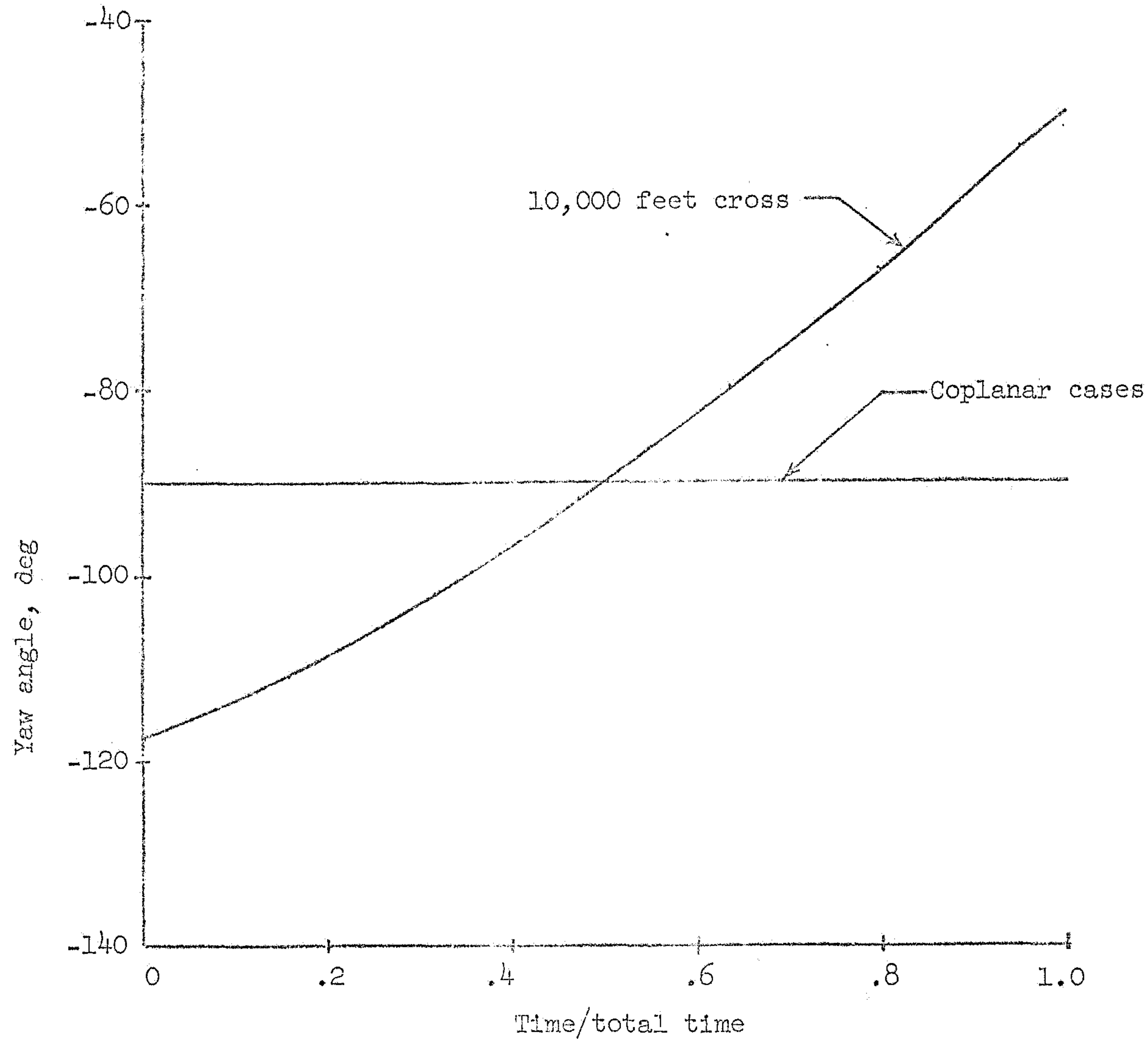

Figure 7 - (Concluded)
(c) Yaw Angle

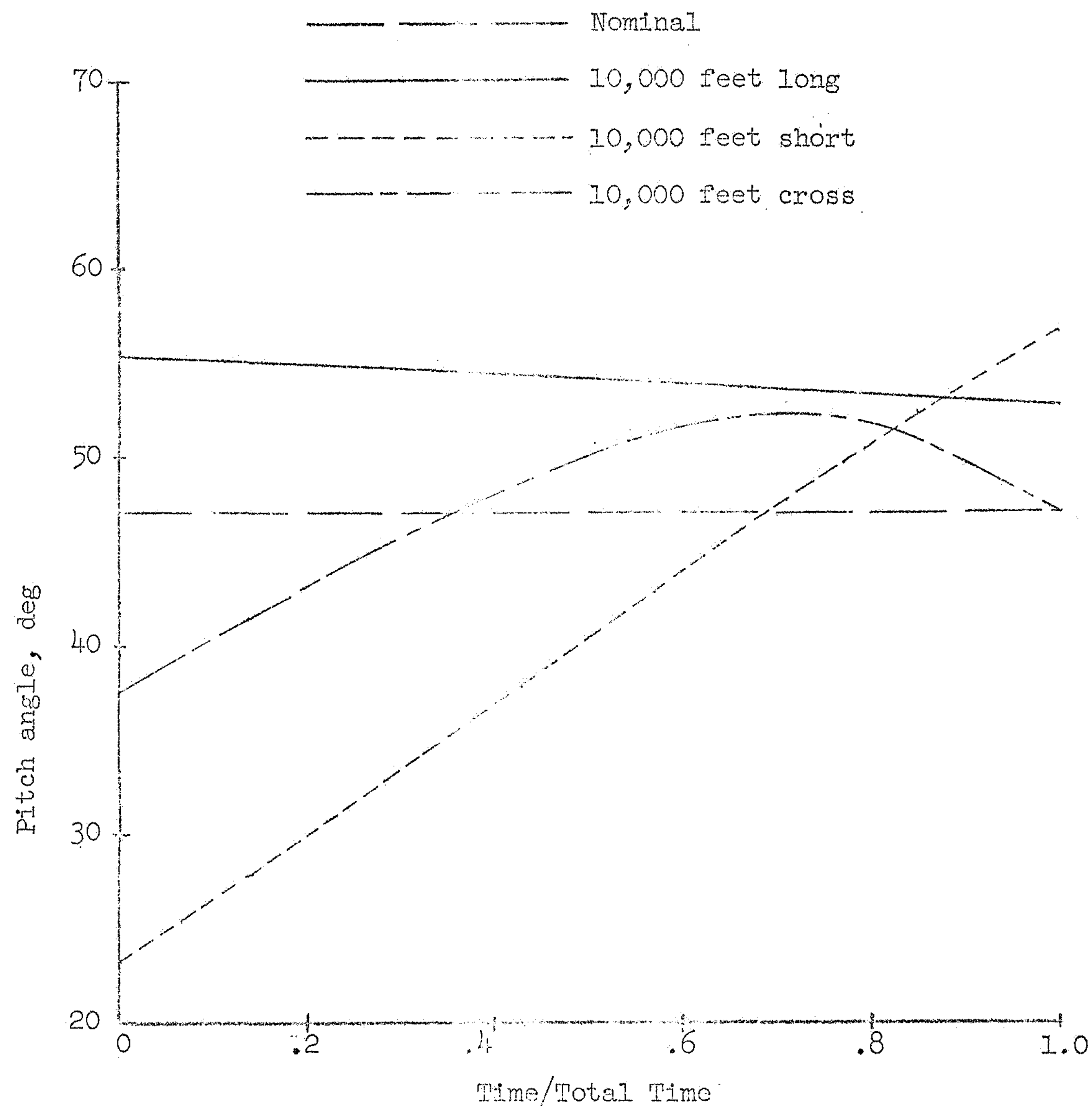

Figure 8.- Time history of guidance commands for alternate site selection from range = 30,492

(a) Pitch Angle

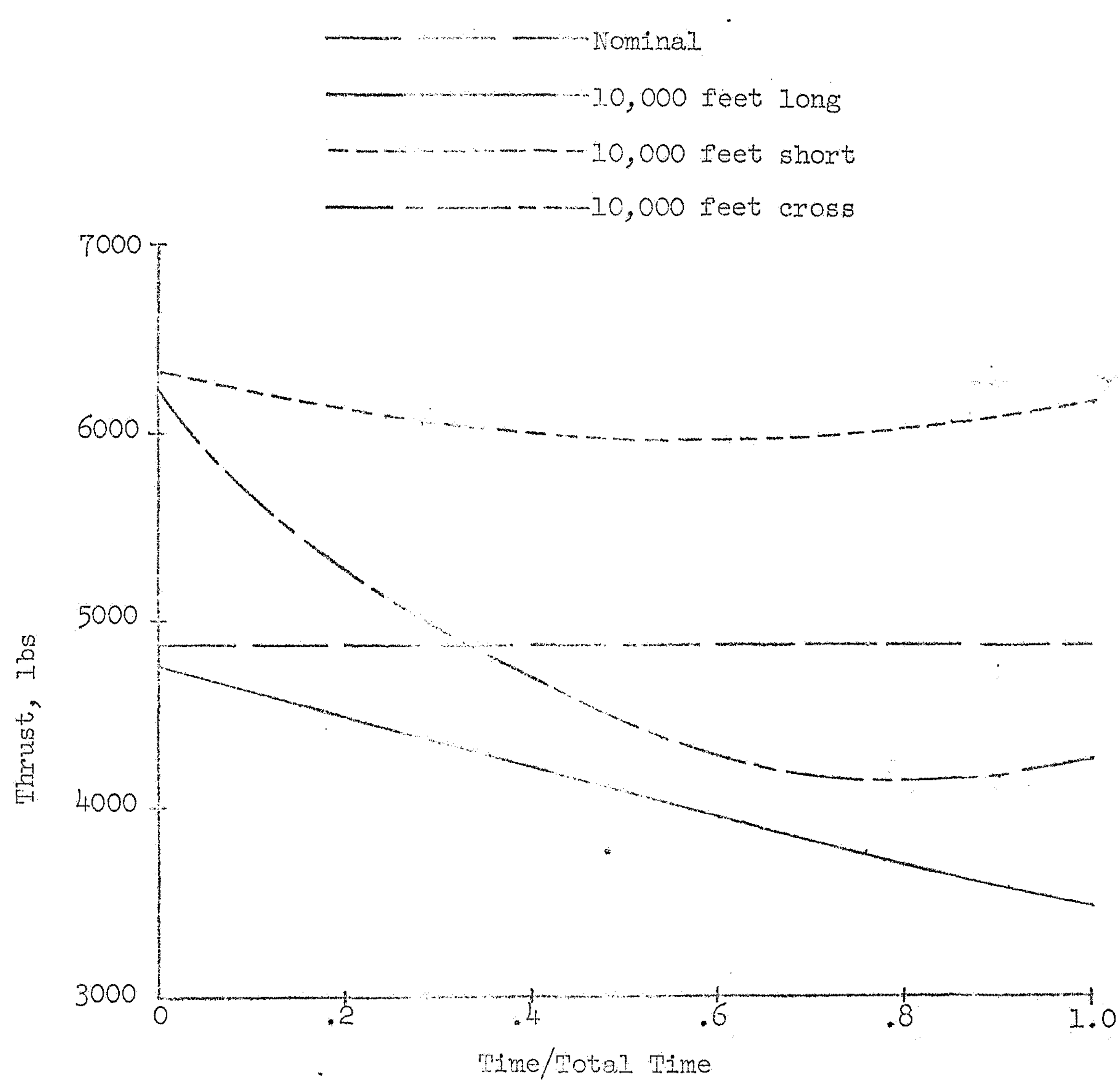

Figure 8 - (Continued)
(b) Thrust magnitude

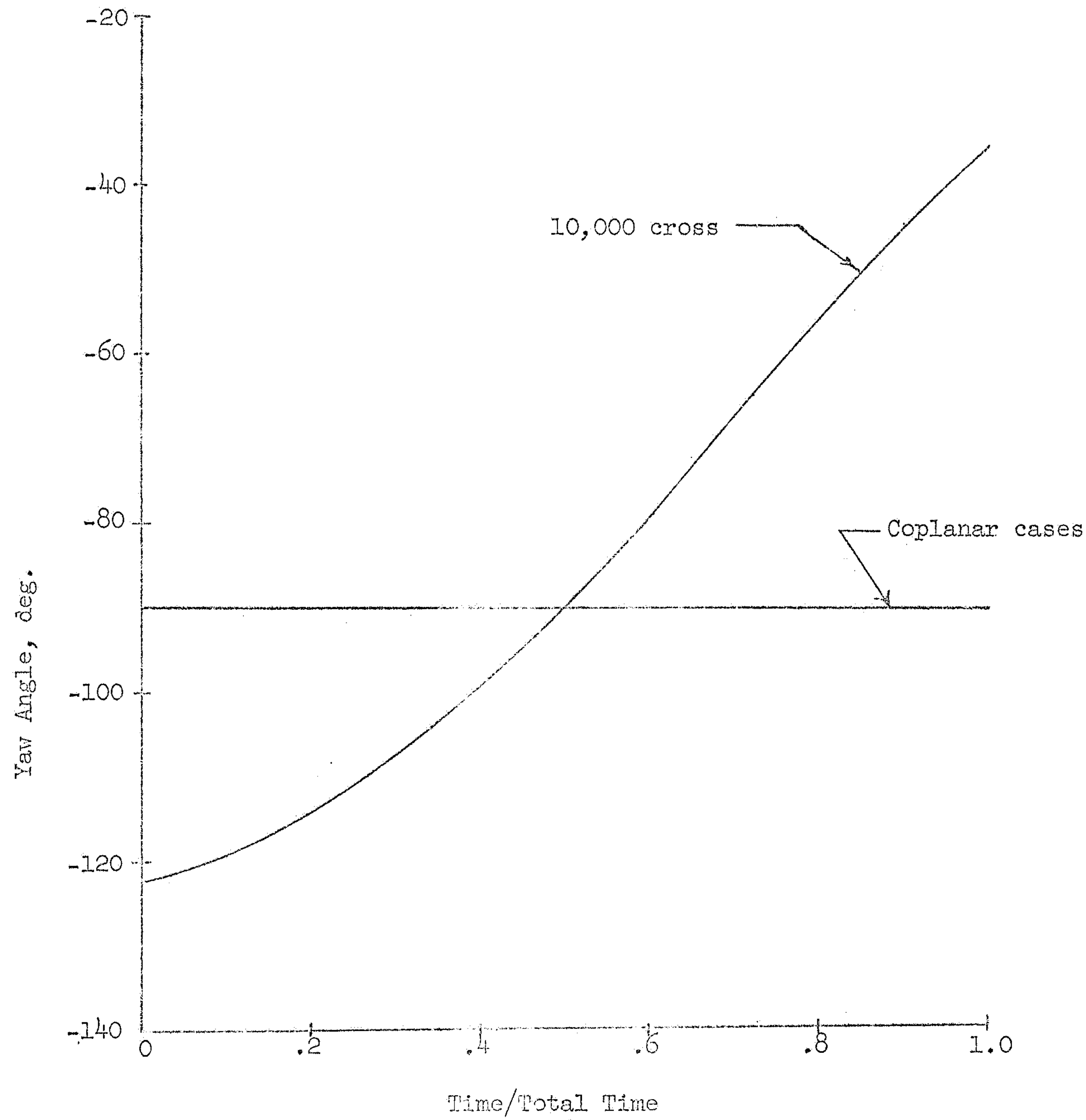

Figure 8.- (Concluded)

(c) Yaw Angle

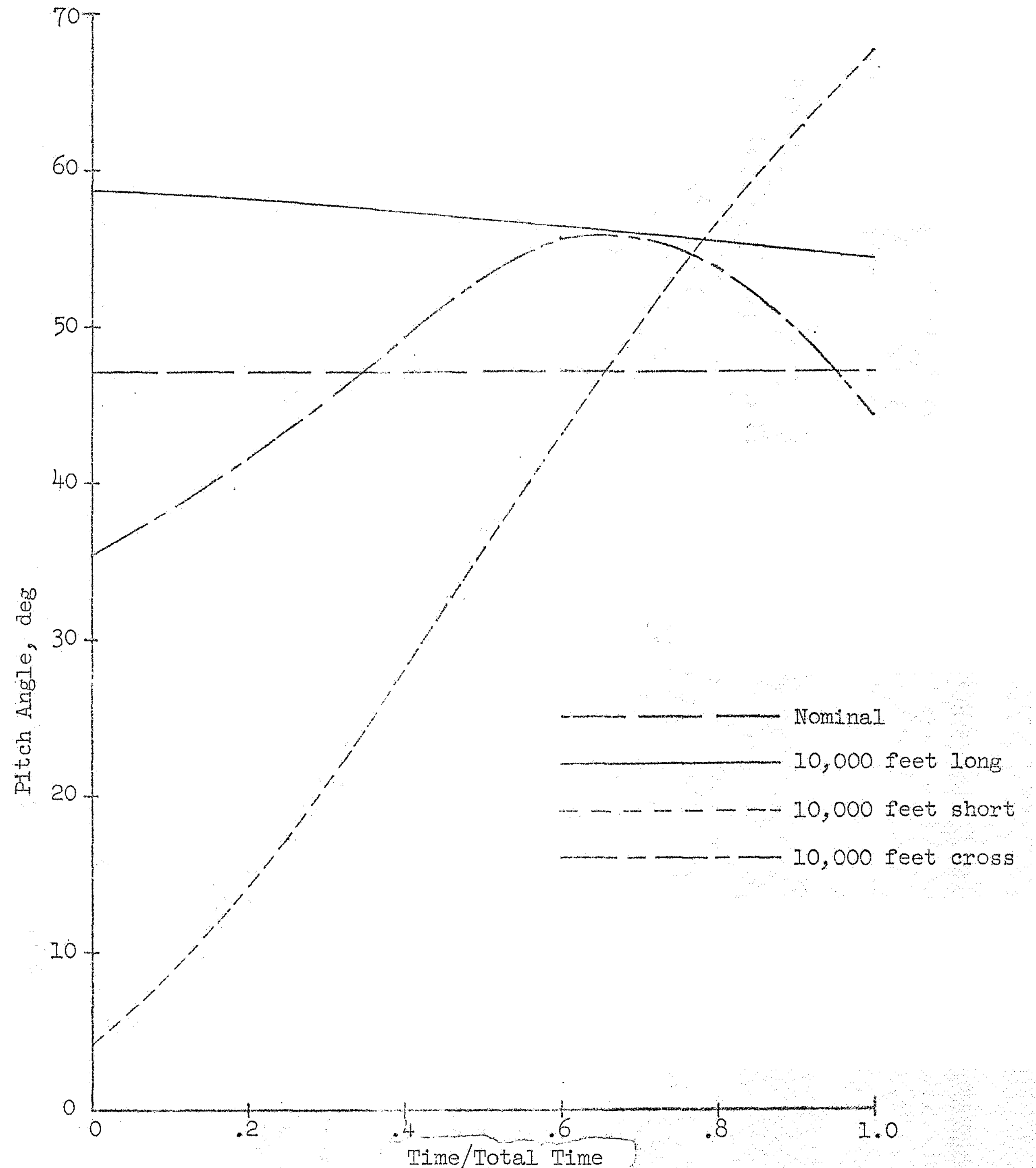

Figure 9.- Time history of guidance commands for alternate site selection from range = 19,510 feet.

(a) Pitch Angle

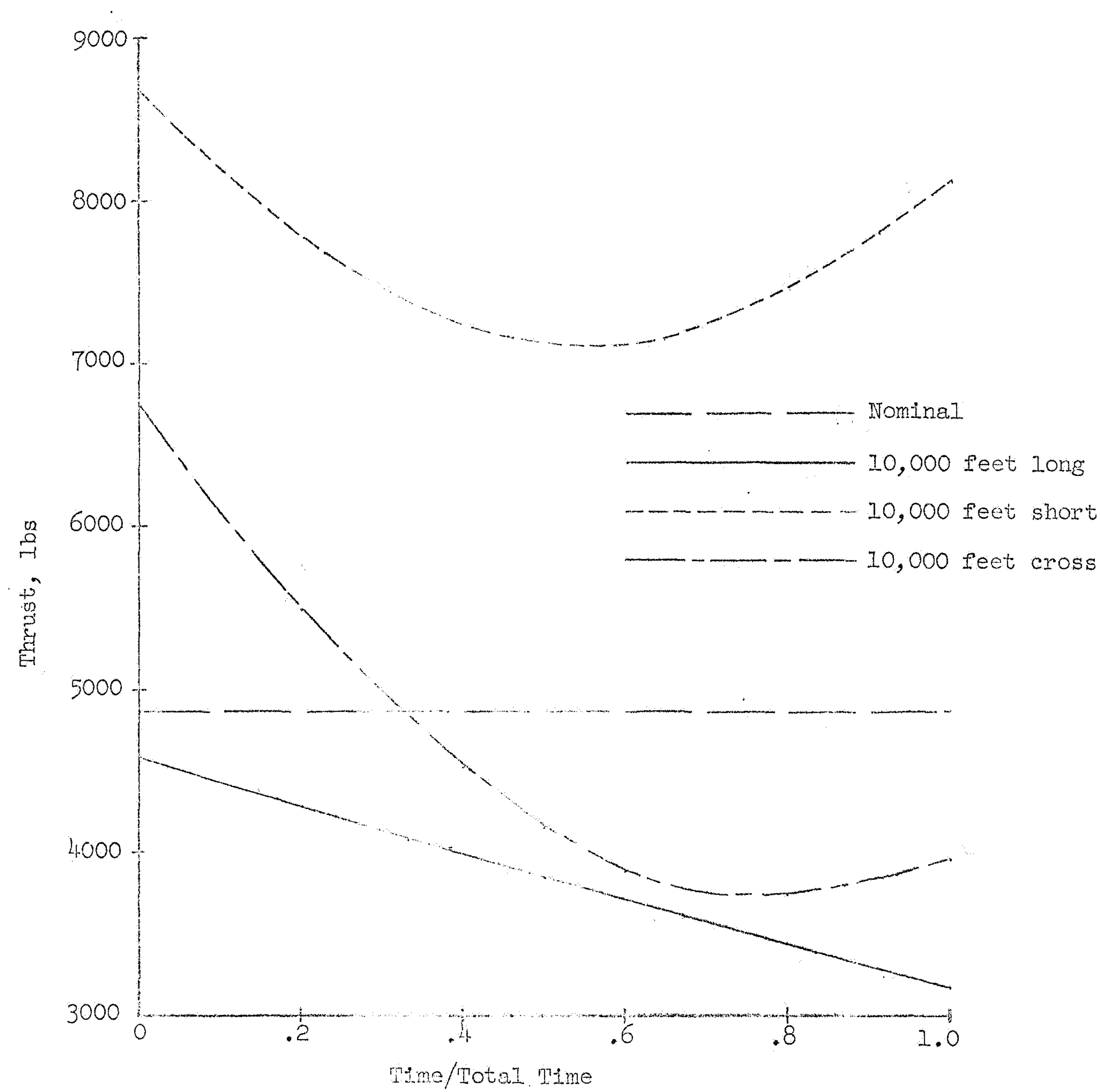

Figure 9 - (Continued)
(b) Thrust Magnitude

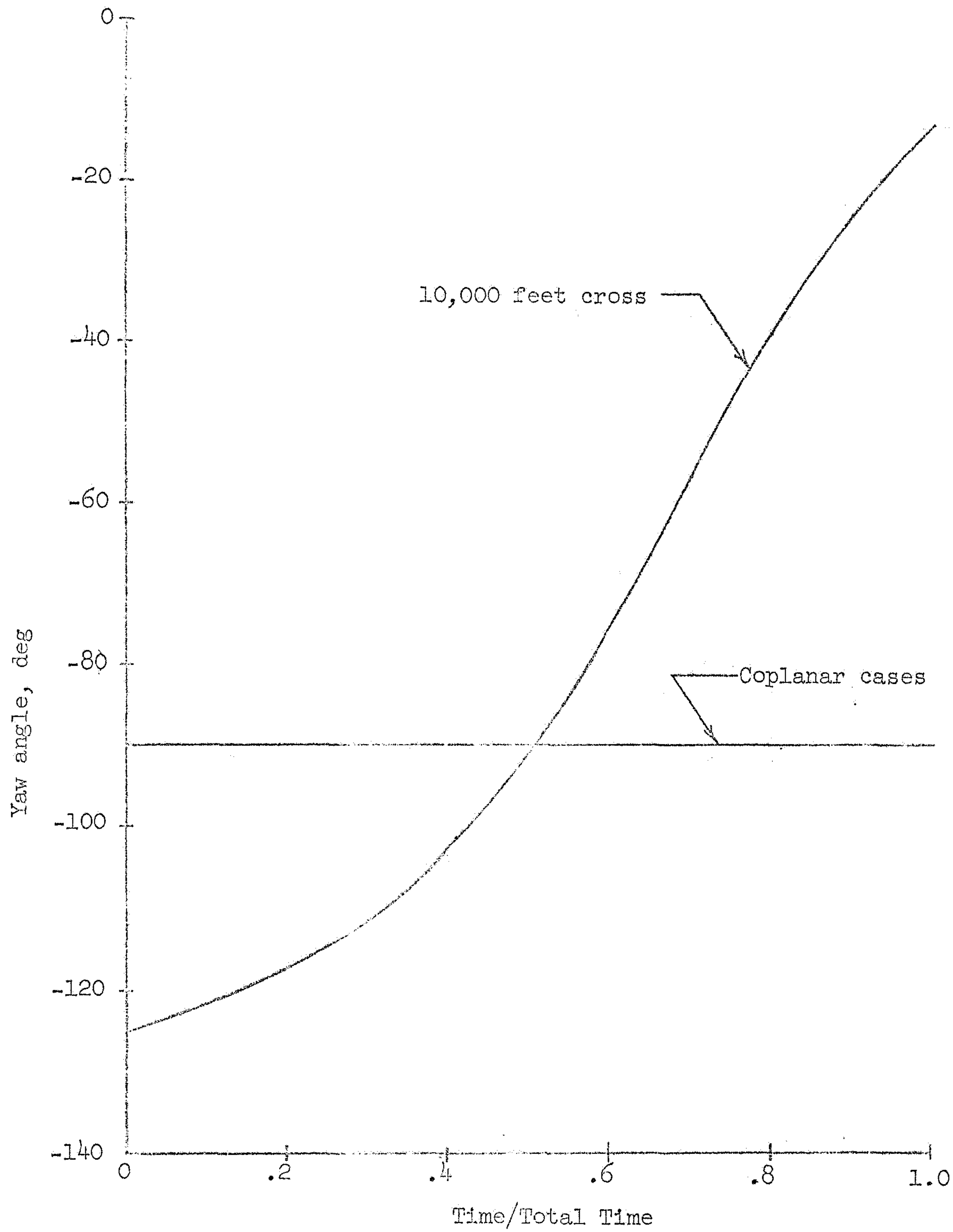

Figure 9 - (Concluded)
(c) Yaw Angle

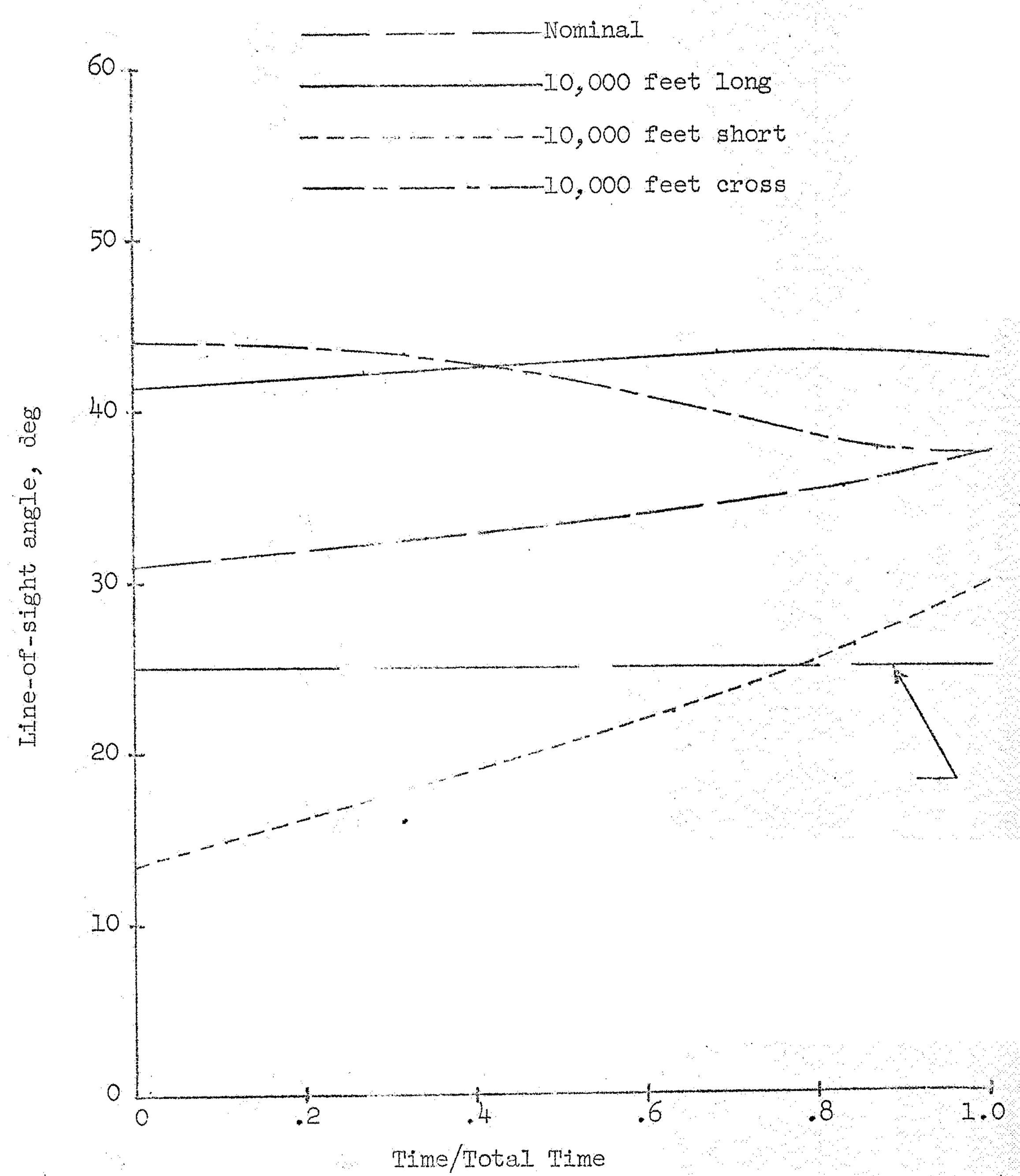

Figure 10.- Time history of line-of-sight angle for alternate site selection
(a) Range = 43,607 feet

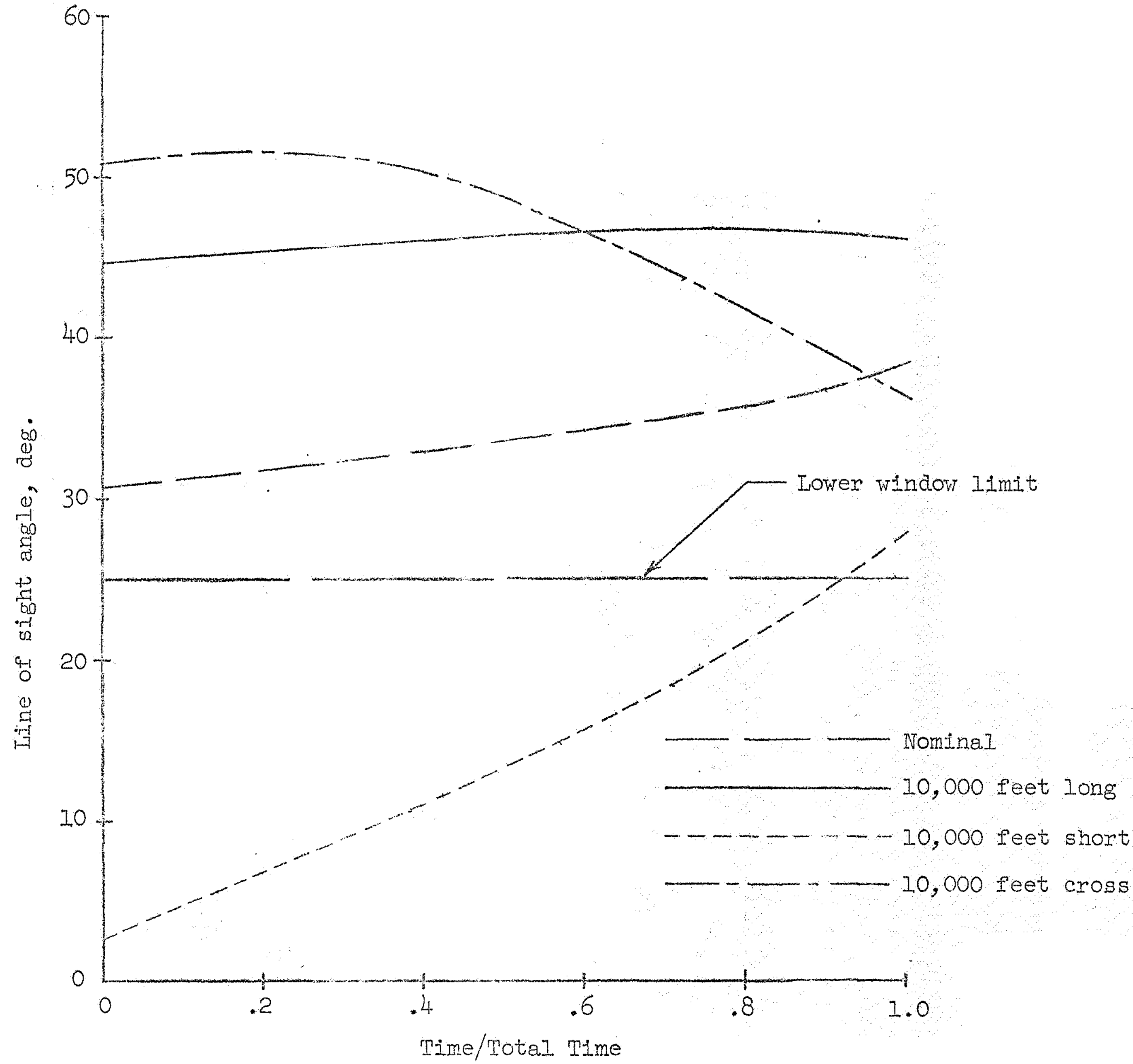

Figure 10.- (Continued)

(b) Range = 30,492 feet

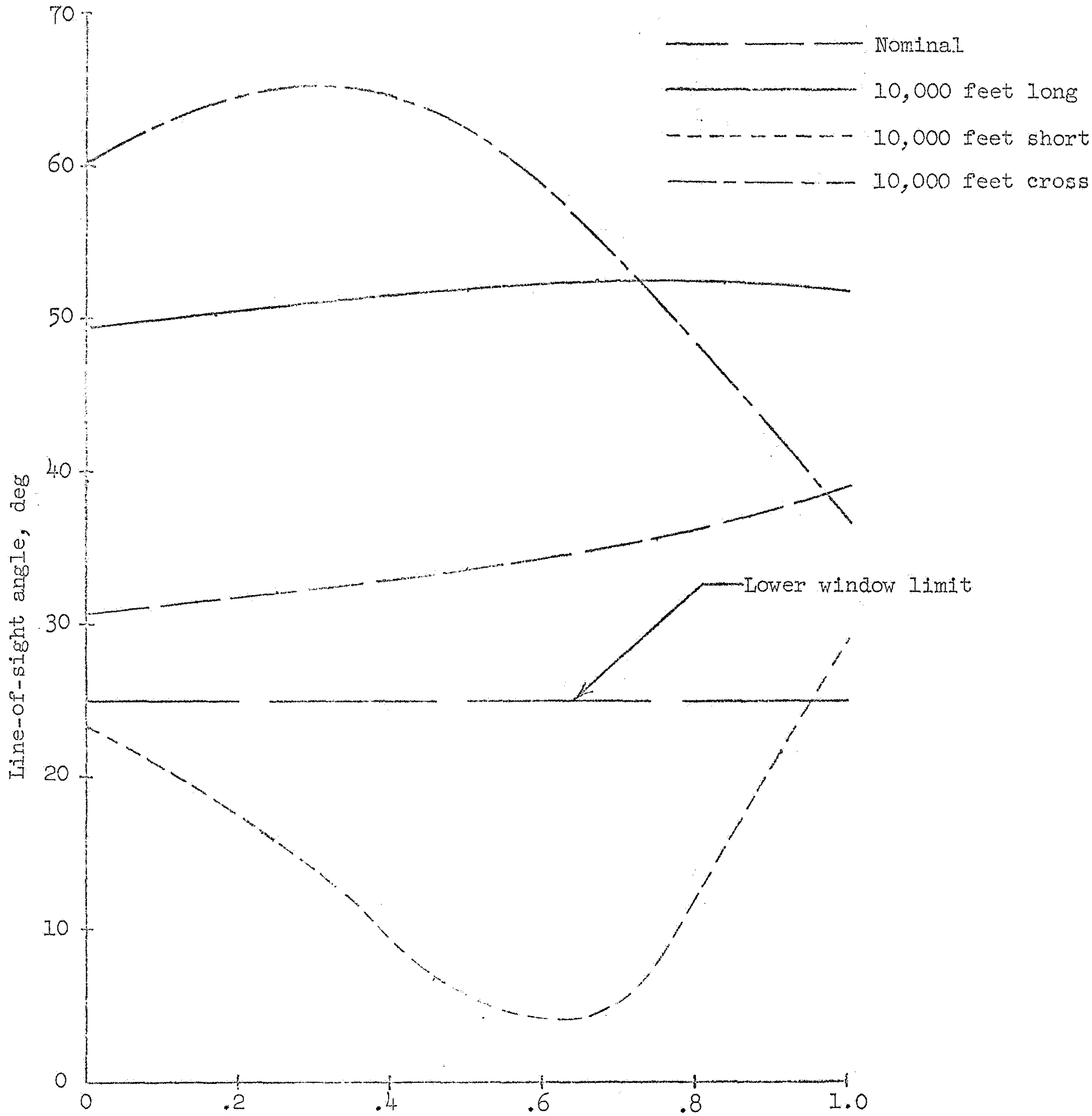

Figure 10.- (Concluded)
(c) Range = 19,510 feet